Structural and Geological Elements of Teide Volcanic Complex: Rift Zones and Gravitational Collapses

4

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Abstract

Initially recognised in the Hawaiian Islands, volcanic rift zones and associated giant landslides have been extensively studied in the Canaries, where several of their more significant structural and genetic elements have been established. Almost 3,000 km of water tunnels (*galerías*) that exist in the western Canaries provide a unique possibility to access the deep structure of the island edifices. Recent work shows that rift zones to control the construction of the islands, possibly from the initial stages of island development, form the main relief features (shape and topography), and concentrate eruptive activity, making them crucial elements in defining the distribution of volcanic hazards on ocean islands.

4.1 Introduction

Rift zones constitute the most pronounced and persistent structures in the development of oceanic volcanic islands because they: (1) control the construction of the insular edifices, possibly from the initial stages; (2) form the main relief features (shape and topography); (3) concentrate eruptive activity; (4) frequently play a key role in the generation of flank collapses and the catastrophic disruption of well-established volcano plumbing systems; (5) are crucial structures in the distribution of volcanic hazards; and (6) condition the storage of natural resources, such as groundwater (Navarro and Farrujia 1989).

Although rifts were initially recognized on the Hawaiian Islands (Fiske and Jackson 1972; Swanson et al. 1976; Walker 1986, 1987, 1992; Dieterich 1988), a good part of the progress made in understanding their genesis and structure has been achieved through their study in the Canary Islands (Carracedo 1975, 1979, 1994, 1996, 1999; Carracedo et al. 1992, 1998, 2001, 2007, 2011; Guillou et al. 1996; Walter and Schmincke 2002; Delcamp et al. 2010).

Compared with those of the Hawaiian Islands, the rifts of the Canaries are considerably longer lasting, exert greater overall control on the construction of the islands, and present more pronounced elements of relief. The lower magmatic activity of the mantle plume or hotspot

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Fig. 4.1 Panoramic view from the top of Pico Viejo Volcano onto the North West Rift Zone of Tenerife, an excellent example of the evolution of a recent volcanic rift. The Teno Miocene Shield outcrops in the far distance (about 20 km)

that has generated the Canaries produces much lower eruptive rates (Geldmacher et al. 2001). This favours higher-aspect-ratio rift zones by accumulation of relatively short flows, promoting the growth of prominent ridges in the relief of these islands (Fig. 4.1). The very low drift velocity of the African plate and the apparent lack of significant subsidence of the Canaries allow for long periods of subaerial activity of the islands (at least 22 My), with corresponding long-lasting rifts that frequently display recurrent activity (Carracedo et al. 1998, 2011).

4.2 Oceanic Rift Zones. What are They and What Do They Represent?

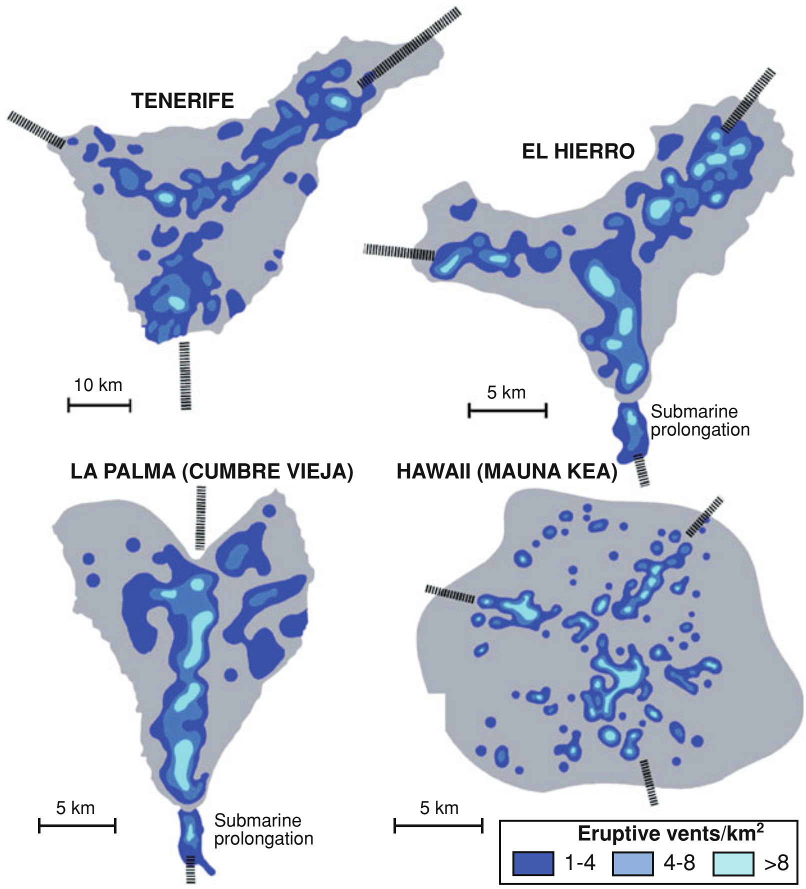
Elongate zones where eruptive vents concentrate to form ridges are common and very pronounced features of oceanic volcanoes. Where erosion has incised sufficiently deeply into these features, their internal structure appears as a dense swarm of dykes broadly parallel to the axis of the ridge, forming "coherent intrusion complexes" (Walker 1992) or "rift zones" (Fiske and Jackson 1972; Carracedo 1975, 1994; Swanson et al. 1976; Wyss 1980; Stillman 1987). This swarm of dykes generally shows a gaussian distribution, with the intrusion density falling rapidly to near zero at the margins of the complexes. A similar pattern is apparent in the distribution of eruptive vents in the ridges (Fig. 4.2).

A high concentration of dykes in the rift zones was first deduced by MacFarlane and Ridley (1968) from conspicuous gravity ridges in the Bouguer anomaly map of Tenerife (Fig. 4.3). According to these authors, the growth of the island was largely controlled (both subaerial and submarine parts) by dyke injection along three major rift zones, with angles of about 120° between them. This idea was also applied by Macdonald (1972) to explain the ground plan, shape and internal structure of the Hawaiian shields.

Detailed studies of these features have been carried out on the Hawaiian volcanoes since the 1960s (Macdonald 1965; Fiske and Jackson 1972; Macdonald 1972; Swanson et al. 1976; Walker 1986, 1987, 1992; Dieterich 1988). Eventually, Walker (1992) defined rift zones as the surficial expression of vents and eruptive sites fed by dyke complexes at depth, pointing out that these structures may be an invariable characteristic of ocean volcanoes.

A significant advancement in the understanding of oceanic rifts has been attained in the Canary Islands, particularly on El Hierro, La Palma and Tenerife from the 1990s onward (Carracedo 1994, 1996, 1999; Guillou et al. 1996; Carracedo et al. 1999, 2007, 2011; Gee et al. 2001; Walter and Schmincke 2002; Walter and Troll 2003; Walter et al. 2005; Delcamp et al. 2010). This work took advantage of the numerous water tunnels in Tenerife and La Palma used for groundwater mining (locally called "*galerías*", 2×2 m and several kilometres long, with a combined length for both islands exceeding 3,000 km). These *galerías* facilitate access to the deep structure of the rift zones, providing a unique opportunity for direct observations and sampling (see Fig. 4.3 in Carracedo 1994).

Fig. 4.2 Concentration of Quaternary eruptive centres in Tenerife, El Hierro, La Palma (Cumbre Vieja), and Hawaii (Mauna Kea). Mauna Kea data from Porter (1972)



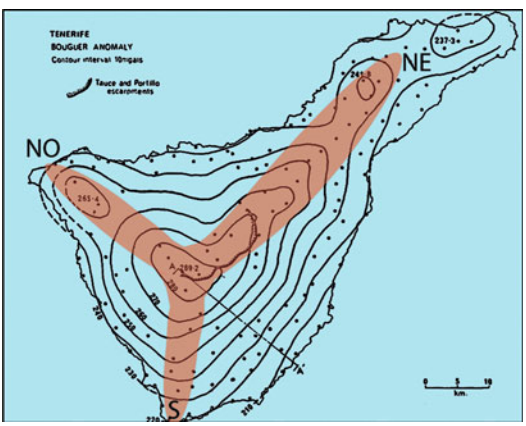


Fig. 4.3 Bouguer anomaly map of Tenerife showing a three-pointed star shape (from MacFarlane and Ridley 1968)

The Taburiente shield and Cumbre Vieja Volcano, both on the island of La Palma, are end-members in the evolutionary stages of rift zones. There, an old and extinct (Plio-Pleistocene) deeply eroded dyke complex (Taburiente), and a recent (<125 ky), active rift zone (Cumbre Vieja) make up the key architectural elements of the island. The latter allows observation of the surface distribution of eruptive vents in these situations, and their main eruptive facies (1 in Fig. 4.4). This comprises a volcanoclastic facies (Fig. 4.4) at the central axis of the rift, and a lava facies (lf) at the flanks of the structure. Deeper in the rift zone, there appears to be a dense group of dykes, oriented approximately along the rift axis (2 in Fig. 4.4). These dykes are the conduits feeding the eruptive vents of the rift, although part of them probably never reaches the surface (Gudmundsson et al. 1999). The internal organisation of the dyke complex can be observed at the floor of the Caldera de Taburiente, where a lateral collapse exposed the core of the shield (3 in Fig. 4.4). The root of the dyke complex is

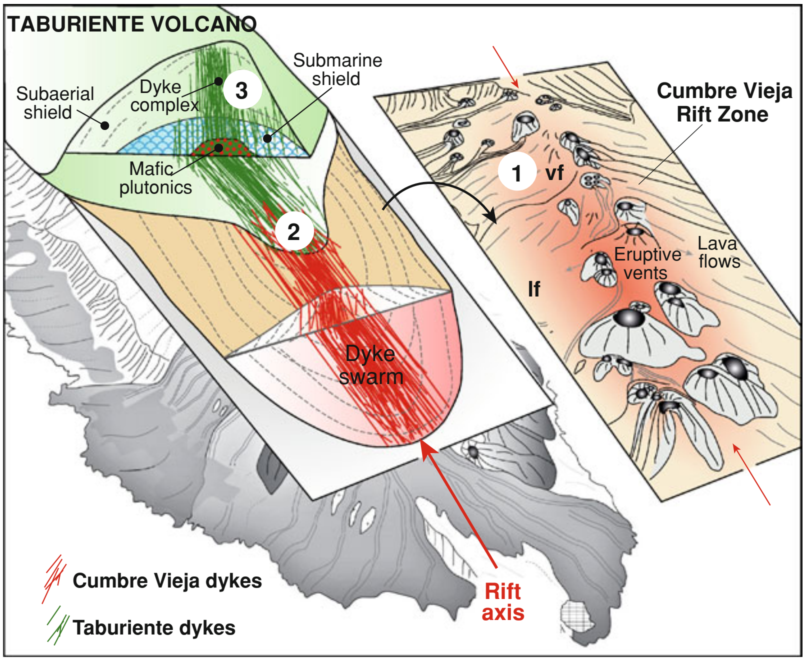


Fig. 4.4 Anatomy of oceanic rift zones: Cumbre Vieja, La Palma. The successive layers show the internal structure of rift zones, from the tight cluster of eruptive vents at the surface of the ridge, to the dyke swarm and the cumulate and plutonic rocks in the deeper part of the structure

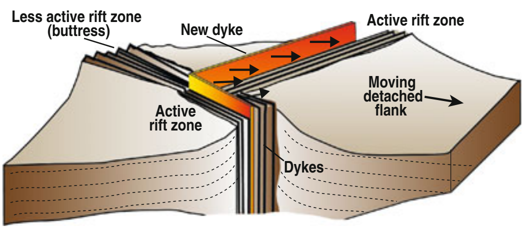


Fig. 4.5 In triaxial rift zones, two of the three arms are usually more active, the third acting as a buttress. Repetitive injections into the active rifts force the enclosed block between these rift arms outwards opposing the buttress and, eventually cause collapse

formed by a plexus of mafic plutonics and cumulates related to the magma chambers and pockets that supply the overlying rift eruptions.

Repetitive injection of blade-like dykes progressively increases the anisotropy of the complex, forcing new dykes to wedge their path parallel to the intrusions (like a knife between the pages of a book, Fig. 4.5). If this process is sustained and if injections are sufficiently frequent, parts of the rift zones may remain hot (thermal memory) to preferentially guide the path of successive intrusions (e.g., Vogt and Smoot 1984). However, intrusion can only progress in a dyke complex if the structure can accommodate fresh injections. Since repetitive intrusion would progressively increase compressive stresses, new injections can only occur if either flank of the rift zone is free to move apart (see Fig. 4.5). Therefore, extensional forces add up in growing rift zones and eventually reach a critical rupture threshold that can trigger massive landslides.

4.3 Development of Rift Zones

Rifts in ocean-island settings can represent the surface expression of initial plume-related fracturing, in response to vertical upward loading (MacFarlane and Ridley 1968; Wyss 1980; Luongo et al. 1991; Carracedo 1994, 1996) and/or extensional fissures due to volcano instability and spread, which develop once a volcano has grown to a certain height and instability (Walter and Troll 2003; Walter et al. 2005; Delcamp et al. 2010, 2012).

Despite advances in the understanding of volcano deformation, it remains unclear how particular rift zones develop. Fractures and rift zones in Tenerife have repeatedly developed in triaxial patterns. These triple-armed rifts are thought to result from magmatic doming, and thus slight upward bending of the crust (Carracedo 1994), or gravitational spreading effects (Walter 2003; Walter and Troll 2003; Walter et al. 2005). Several such "triaxial rift zones" exist on the island (as also on El Hierro), some of which were active simultaneously.

Endogenously driven mechanisms are thought to play a major role in establishing axial volcano architectures. Plumes typically cause uplift that ruptures the rigid oceanic plate along three rifts meeting at triple junctions. Commonly, two of these rifts become a plate boundary (either a ridge or a ridge/transform) while the third does not spread and becomes a failed arm. A similar mechanism was postulated by D'Albore and Luongo (2009) and Luongo et al. (1991) for the tectonic structures of the Neapolitan area, with the Phlegraean Fields occupying the centre of a triple junction generated by a rising crustal tumescence (a plume). The regular triple-armed junctions and triaxial rift zones on volcanoes would then result from the least-effort fracturing of the brittle crust at 120° angles (Luongo et al. 1991; Carracedo 1994, 1996). This least-effort model (Fig. 4.6) is considered to explain (a) the aligned concentration of eruptive sites on the Canaries (Tenerife, El Hierro and La Palma), (b) the longevity and direction of rift zones, and (c) the genesis of volcano sector collapses located in-between 2–120° rift arms (Carracedo 1994, 1996). In this model, the rift zones are thought to have initiated early in the history of the islands and form their deep inner structure.

However, important objections to this model have been raised. If triaxial rift zones developed simultaneously on particular islands (e.g., Tenerife, Hawaii) the location of the centres of those rift systems should be sufficiently distant from each other considering the highly viscous relaxation behaviour of the upper mantle and flexure wavelengths of the crust (Watts and Masson 2001). If Tenerife shield volcanoes (Teno, Anaga and Central shields) are thought to be triaxial structures, they are probably located too close to one another to meet those conditions (Walter and Troll 2003).

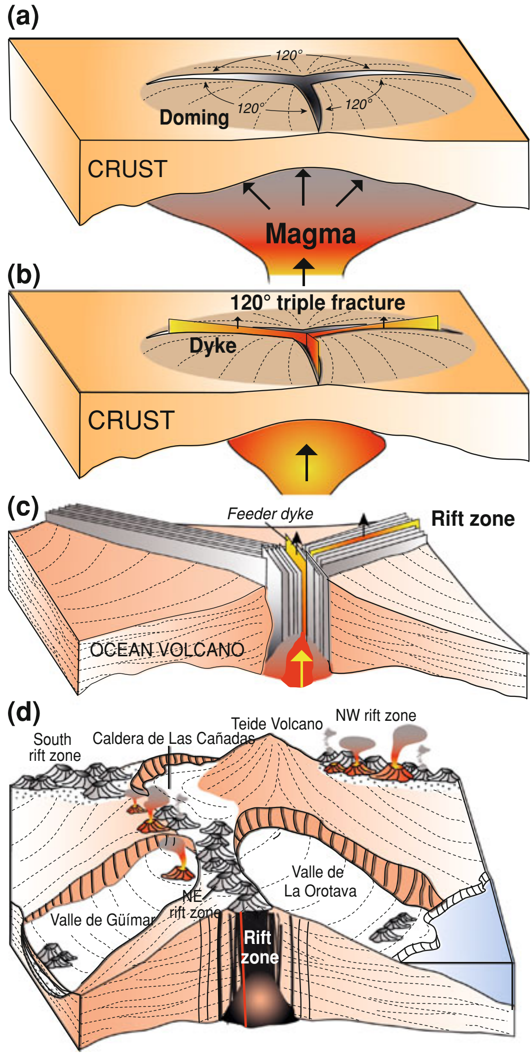


Fig. 4.6 Model proposed by Carracedo (1994, 1996) linking volcanic rift zones and landsliding in the Canary Islands. Three-armed rifts, spaced at ~120°, seem to be the naturally preferred configuration, as in the case of El Hierro and Tenerife. This architecture is thought to be a response to least-effort fracturing. The resulting three-sided base pyramidal edifice geometry may be further enhanced by landsliding between the rift arms, propagating perpendicular to the rift direction

An alternative process is that flank deformation is caused by rifting, once a volcano becomes sufficiently unstable for dyke intrusions to force the flanks of the volcano to spread and

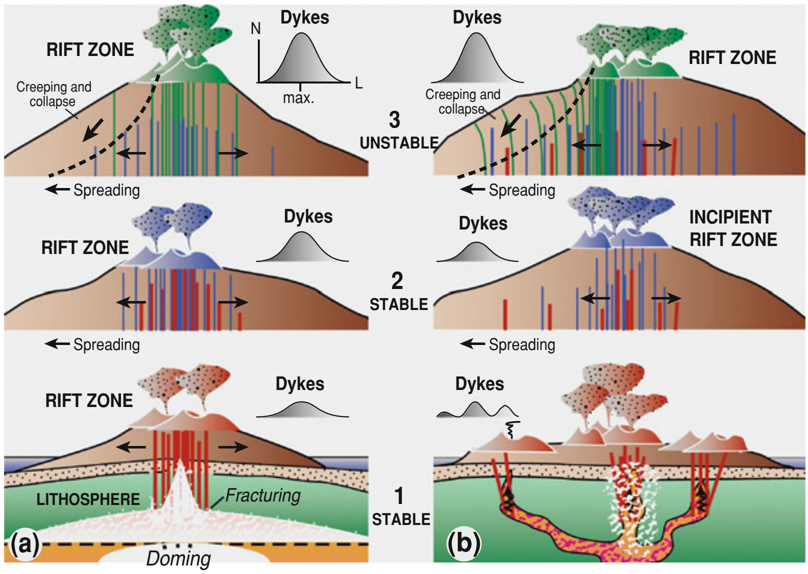


Fig. 4.7 Whether rifting is a consequence of deformation from plume-derived updoming and fracturing (**a**), or rifting (forceful intrusion) causes a flank to deform by creeping and spreading (**b**), the final result of both processes is convergent. There are pros and cons for both models and no definitive evidence favours either of them. In fact, both types of rift zones may be present in the Canaries, with type A predominant in the early stages of construction of the island volcanoes and type B becoming more prevalent in the latter stages of rift development. *N* number of dykes; *L* distance across the rift

creep seaward (McGuire et al. 1990; Elsworth and Voight 1995; Iverson 1995; Elsworth and Voight 1996; Delcamp et al. 2010). Therefore, the question arises whether rifting is a consequence of flank deformation, or rifting causes a flank to deform. Both models (a and b in Fig. 4.7) have a completely different initiation, but the final results are similar. Therefore, multiple rift systems may develop differently. Triple-armed rift zones can result from the least-effort fracturing of the brittle crust (see a in Fig. 4.7), at the initial stages of development of a particular island (e.g., the Central Shield of Tenerife) where plume-related or oceanic fractures may provide important magma pathways (e.g., Carracedo 1994; Geyer and Martí 2010; Carracedo et al. 2011). Alternatively, ridge-like volcanoes have been shown to develop a third arm once the edifice has matured and developed instabilities. Then, a more passive rift arm may open opposite the collapse scar due to extensional stresses (e.g., Walter and Troll 2003; Walter et al. 2005).

Observations on Tenerife and El Hierro shields as well as in analogue gelatine experiments have shown that slight eccentricity of the creeping sector focuses dyke intrusion along two curved axes tangential to the stable/unstable interface. In contrast, strong eccentricity results in only one main tangential rift, while other rifts remain poorly developed (Walter and Troll 2003; Walter et al. 2005). With initiation of a creeping sector, an initially radial or ridge-like geometry is likely to reconfigure and produce rift-zones that will lead to additional rift arms. The most common arrangement resulting from such geometry would be another (third) arm to form the frequent triple-armed systems. Intrusion into the margin between stable and unstable sectors may thus favour the triple-armed configuration.

This architectural evolution may be illustrated in the development of the Taburiente shield in the early subaerial construction of La Palma, where rift zones seem to have progressed from an initial disperse radial distribution of eruptive vents (Fig. 4.8). Southward migration

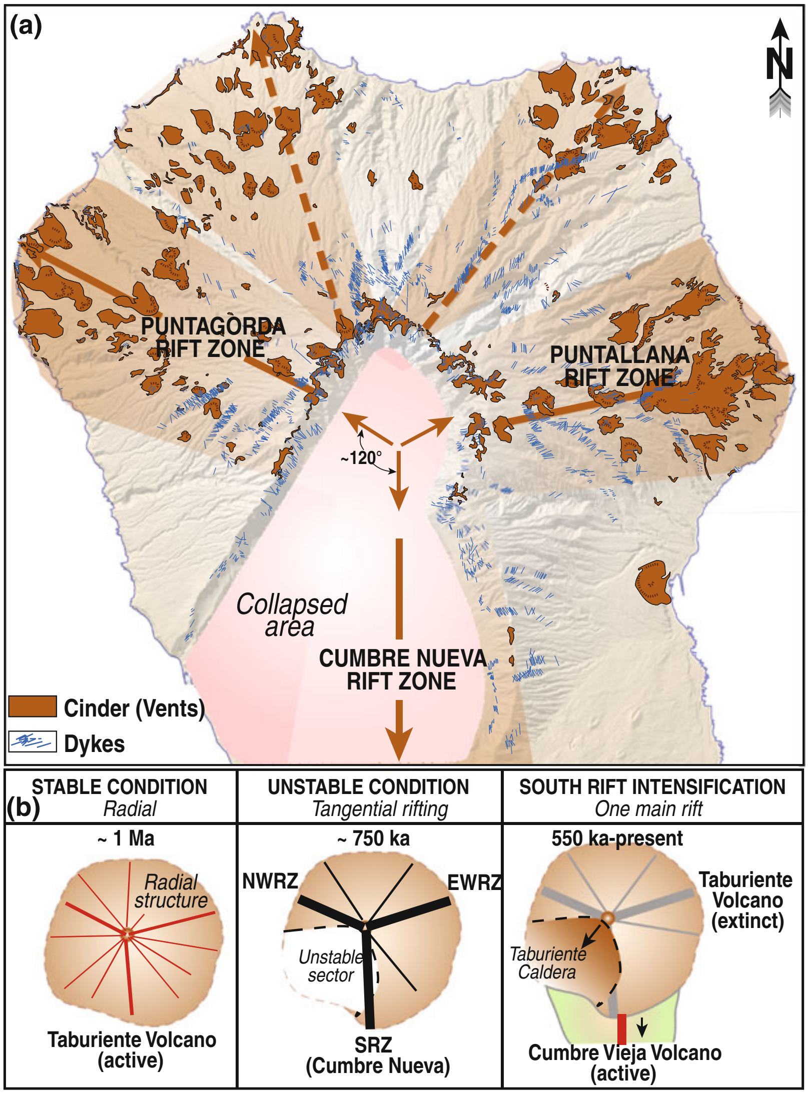


Fig. 4.8 **a** Eruptive vents and dyke outcrops of the Taburiente shield volcano (~0.77–0.4 Ma), La Palma, with rift zones forming a radial structure. The incipient three-armed rift organisation (*solid lines*) was apparently left incomplete by the extinction of Taburiente Volcano at an early stage of development (from Carracedo et al. 2001). **b** Stages of structural evolution of La Palma from an initial radial structure. The position and direction of the creeping flank favoured extension in an east–west direction on the southern flank, and thus the formation of a north–south rift zone. Once formed, the main south rift stabilized by the alternation of constructive and destructive processes such as volcanism, landsliding and erosion (modified from Walter and Troll 2003)

of volcanism left the shield extinct and probably interrupted the organisation of rift zones (Carracedo et al. 2001). Conversely, regular long-lived triaxial rift zones develop where magma plumbing remains stationary, e.g., the Central Miocene Shield and the Plio-Pleistocene Las Cañadas Volcano, in Tenerife (Fig. 4.9).

Analogue gelatine and sand-box experiments confirm the generation of a triangular system of conjugate graben axes in settings reproducing the steady conditions of El Hierro (Fig. 4.10), where magma plumbing apparently has remained stationary, suggesting that these triaxial rift zones may be a late reconfiguration as a progressive response to volcano deformation (Walter and Troll 2003; Münn et al. 2006). However, observations in *galerías* in the central part of Tenerife show that the dyke complex of the Miocene Central Volcano follows broadly the very same orientation as the rift zones that developed during the formation of Las Cañadas Volcano and those of the present day rift zones (Carracedo 1975, 1979).

At present there is no definitive evidence in favour of either of these models—endogenously driven mechanisms or rifting by spreading and

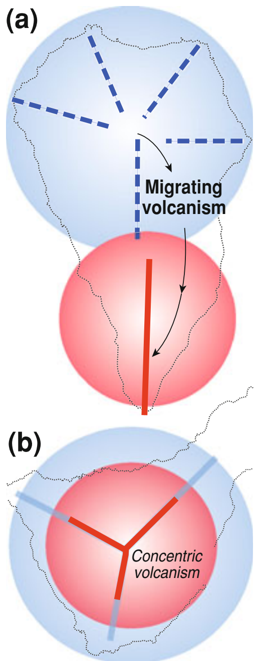


Fig. 4.9 Classical triple-armed rift zones are usually not well developed when moving magmatic sources are involved (e.g., **a** La Palma). A stationary magma supply, however, gives rise to concentrically overlapping volcanoes and well-developed triple-armed rift zones (e.g., **b** Central shield in Tenerife) (modified from Carracedo et al. 2001)

creeping of volcano flanks. Both mechanisms, although very different at the start give similar results. A plausible assumption is that large, deep triple-armed rift zones develop at the early stages of island construction by plume related updoming and fracturing, with later modifications due to volcano edifice stability issues, whereas smaller rift systems (not necessarily multiple) might form entirely from gravitational spreading and associated structural re-arrangements at unstable volcanoes.

4.4 Rift Zones of the Teide Volcanic Complex

The Teide Volcanic Complex provides one of the best possible scenarios to study the characteristics and evolution of rift zones in ocean volcanoes. The North East Rift Zone (NERZ) presents a superb opportunity to study the entire cycle of activity of an oceanic rift zone. This rift, inactive for hundreds of thousands of years along most of its length, has been deeply mass-wasted by erosion and massive landsliding, allowing an in-depth study of its internal structure, including the complex network of dykes exposed (Delcamp et al. 2010; Carracedo et al. 2011). On the other hand, the North West Rift Zone (NWRZ) represents an outstanding example of the latest stages of rift development, demonstrating interesting patterns of spatial and temporal distribution of eruptive vents and associated geochemical and petrological variations (Ablay and Martí 2000; Carracedo et al. 2007), including rare examples of complex magma mixing (Wiesmaier et al. 2011).

4.4.1 The NE Rift Zone

This rift zone extends for about 35 km, from the foot of Teide to the Anaga massif. The deep core of the rift is an extension of the Central Miocene shield towards the Anaga massif (Guillou et al. 2004; Carracedo et al. 2011), outcropping at the NE end of the rift and underlying the Pliocene Anaga Volcano (Fig. 4.11). The present configuration of the NERZ is characteristic of rift structures, with a cluster of eruptive vents forming the crest of the ridge and lava flows at the flanks (Fig. 4.12). Vents are tightly packed at the SW (proximal) end of the rift, whereas at the SE (distal) tail they end and appear dispersed in a characteristic fan distribution. The proximal end of the rift also concentrates the most recent activity. This part actively contributed to the Icod lateral collapse and the evolution of the TVC.

The rift apparently had three successive cycles of activity—in the Miocene, the Pliocene and the Pleistocene (Fig. 4.13). The last one (comprising the last million years) is the best documented and is the only one that is related to the TVC, at least in its final stages. This latest cycle of activity of the NERZ has been coeval with the development of Las Cañadas Volcano, but both volcanoes were clearly interacting, as suggested by sequences of basaltic lapilli from the NERZ alternating with beds of phonolitic pumice from Las Cañadas Volcano. It appears that most recent age dates, in fact, imply that the Anaga shield is younger than the central edifice, making an arrangement of shields to form rift-zones as shown in Fig. 4.10 somewhat unlikely.

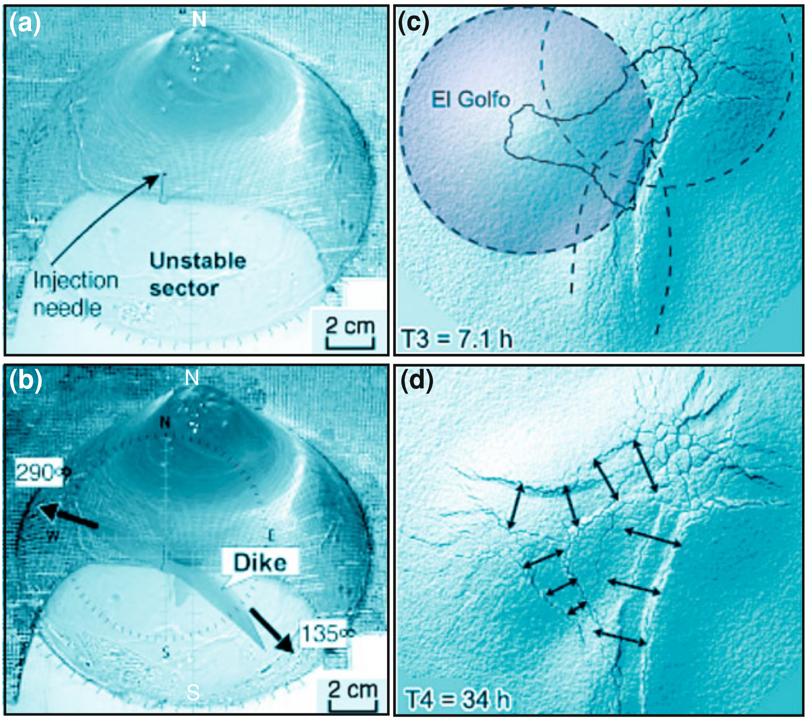


Fig. 4.10 **a**, **b** Scaled analogue experiment with gelatine models. **a** Gelatine cone before injection of a liquid (the magma) into the interface creeping/non-creeping sector and a slight southwestward eccentricity of the lubricated base. **b** After injection, 80 % of the experiments produced a triple-arm intrusion arrangement (Walter and Troll, 2003). **c**, **d** analogue experiment with sand cones simulating the overlapping "Tiñor cone" and the "Southern Ridge" (El Hierro) emplaced simultaneously. After 7.1 h, the "El Golfo cone" was added overlapping the 'Tiñor cone' and the ridge. In **d**, the two cones and the ridge have spread for 34 h showing a triangular system of conjugate graben axes (Munn et al. 2006)

Three reasonably well-dated and documented successive giant landslides in the latest active cycle of the NERZ provide relevant information to understand the genesis and characteristics of mass-wasting processes in oceanic volcanoes, and help to clarify the succession of events giving rise to the formation of the Las Cañadas-Icod-La Guancha collapse depression and the subsequent nested Teide Volcano.

4.4.2 Evolution of the NE Rift Zone

The initial, pre-collapse stages of the latest cycle of activity of the NERZ developed a volcanic ridge that may have reached an altitude of about 2,000 m a.s.l. (Fig. 4.14a). The critical phase of construction was between ca. 1,100 and 860 ky, when the growth rate may have reached 3.5 m/ky, indicating an intense episode of intrusive and eruptive activity leading to the progressive instability of the volcano. This, in turn, led to dykes changing direction in response to the increasing instability at this stage (see e.g., Walter and Troll 2003; Delcamp et al. 2010) from 20° to 40°, the main orientation of intrusions in the NERZ, to 0°–10° at the final stages.

The main constraint for the time of occurrence of the first lateral collapse (Micheque), with an estimated volume assessed from digital elevation model analysis of ~60 km^3, is primarily based on the ages obtained in the Los Dornajos galería (see upper section in Fig. 4.13), which suggests that this collapse must have occurred ca. 830 ky, the age of the first nested lavas above the avalanche breccia. The landslide generated a basin in the north flank of the rift,

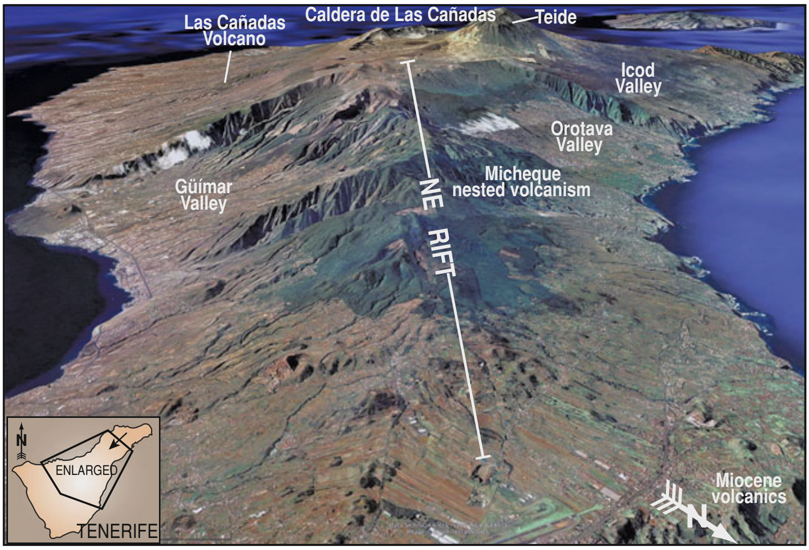


Fig. 4.11 Google Earth image of the NE Rift Zone of Tenerife viewed from the Anaga massif (oblique view of Tenerife from the NE). The rift had already extended in the Miocene from the central edifice of what is now Las Cañadas towards the Miocene-Pliocene Anaga massif. The landslide scars of La Orotava and Güímar are clearly visible, unlike the Micheque landslide, which is completely covered by post-collapse volcanism (image Google Earth)

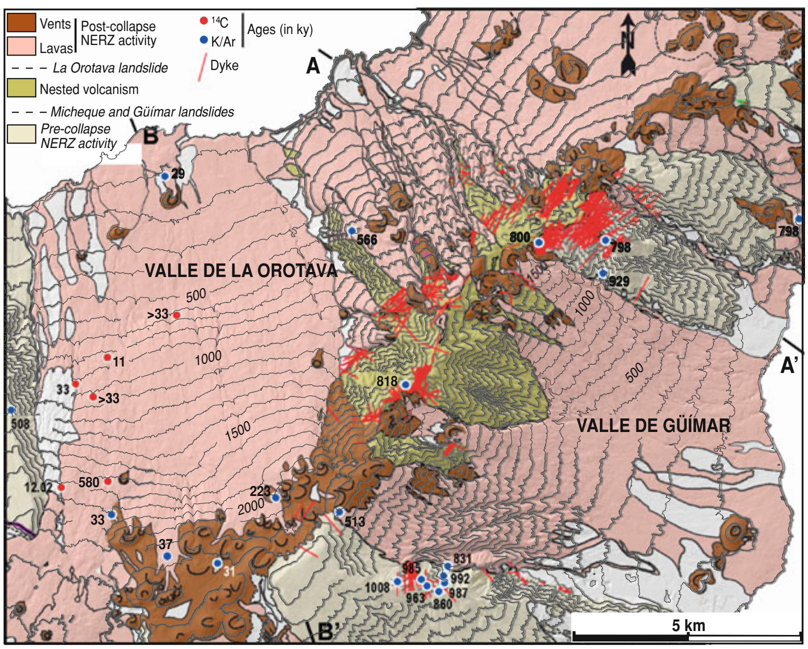


Fig. 4.12 Simplified geological map of the NE Rift Zone of Tenerife showing the distribution of eruptive vents and lava flows. Ages (in ky) from Carracedo et al. (2011)

probably extending towards the present-day valley of La Orotava (Fig. 4.14b). Subsequent volcanism filled large parts of the collapse basin, extending beyond the coastline, concealing the scar and the avalanche breccia to be only found in *galerías* in the northern flank of the rift zone.

A second landslide (the Güímar lateral collapse, estimated volume: 47 km^3), at the east

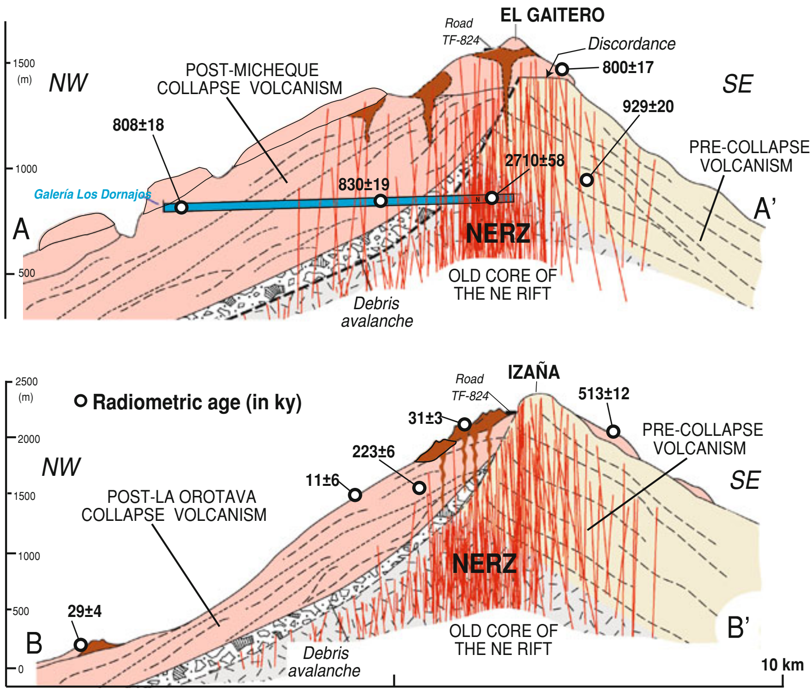


Fig. 4.13 Geological cross-sections of Tenerife (NERZ) perpendicular to the rift axis (compare with Fig. 4.12 for section lines). Two of the lateral collapses (Micheque and La Orotava) are crossed by the sections, showing that the rift zone has been operating for at least for 2.7 Ma. Ages in ky (from Carracedo et al. 2011)

flank of the NERZ, formed a pronounced (10 × 10 km) depression (Fig. 4.14b). The timing of this collapse is constrained by the age of 860 ± 18 ky obtained from lava flows topping the southern collapse scar (Pared de Güímar), and that of the first volcanism nested inside the landslide embayment, dated at 831 ± 18 ky.

The eruptive rate and volume of the Güímar in-fill formations seem much lower than those of the Micheque event. This suggests that, although roughly contemporaneous, the Micheque collapse may have been the first of the two to occur, coinciding with a phase of intense volcanic and intrusive activity. This may point to a fundamental difference in the mechanism that caused the two flank failures: distensive stresses associated with intense eruptive and intrusive activity in the Micheque collapse, and gravitational instability increased by the response to the earlier collapse in the case of the Güímar landslide. This would explain the observation that, by far, the greater part of volcanism continued to be concentrated in the interior of the first, the Micheque collapse, even after the Güímar landslide took place. This caused the total infilling of the Micheque depression and the evolution of significant volumes of magma (0.5–1.0 km^3) towards highly differentiated compositions in this sector (Fig. 4.14c, d).

A third collapse at the northern flank of the NERZ (Orotava lateral collapse, estimated volume: 57 km^3) formed the Orotava Valley (Fig. 4.14d). The relatively accurate dating of the previous collapses has not been achieved in this last case. Its age is constrained by a minimum age of 566 ± 13 ky from lavas of felsic compositions of the Micheque nested volcanism cascading over the eastern scar of the Orotava Valley (Carracedo et al. 2011), and the age of 690 ± 10 ky, obtained by Abdel-Monem et al. (1971) from the lower part of the collapsed sequence at the southern (Tigaiga) scar (Fig. 4.14d). It seems therefore that the Orotava collapse occurred between 690 ± 10 and

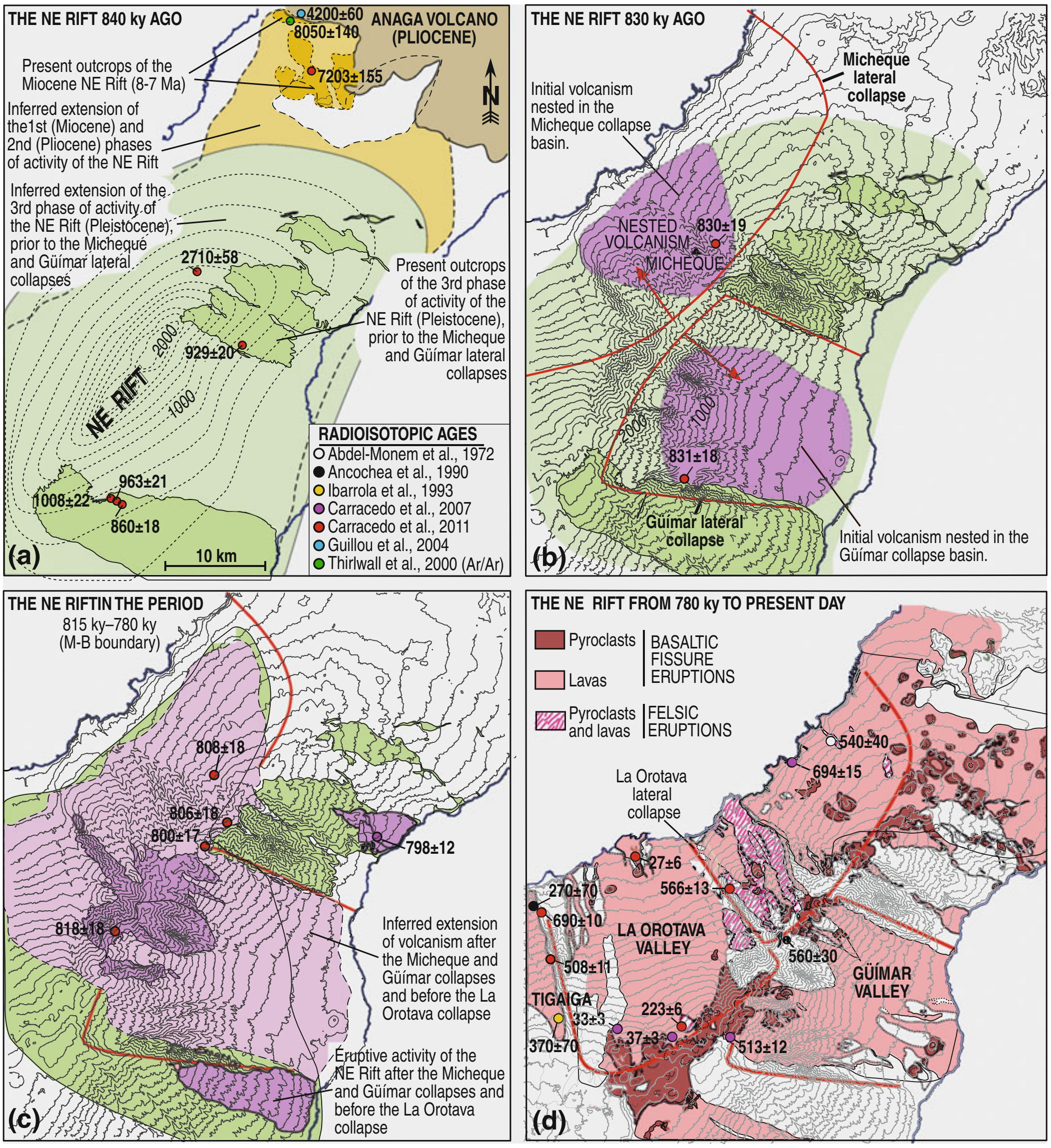


Fig. 4.14 Successive stages of development of the NE Rift Zone of Tenerife (modified from Carracedo et al. 2011; Abdel-Monem et al. 1972; Ibarrola et al. 1993; Thirlwall et al. 2000)

566 ± 13 ky, which places it significantly after the Micheque and Güímar landslides.

4.4.3 Decline and Dispersed Activity of the NERZ

Following the three collapses, the rift entered into a stage of stabilisation and progressively decreasing eruptive activity. Simultaneously, the dispersion of the eruptive centres, previously grouped preferentially at the crest of the rift, increased, particularly at the distal NE end (see Fig. 4.14d). These eruptions, all of normal polarity, have given ages of 513 ± 12 ky (Carracedo et al. 2007), 540 ± 40 ky (Abdel-Monem et al. 1971) and 560 ± 30 ky (Ancochea et al. 1990). NERZ eruptive activity, although

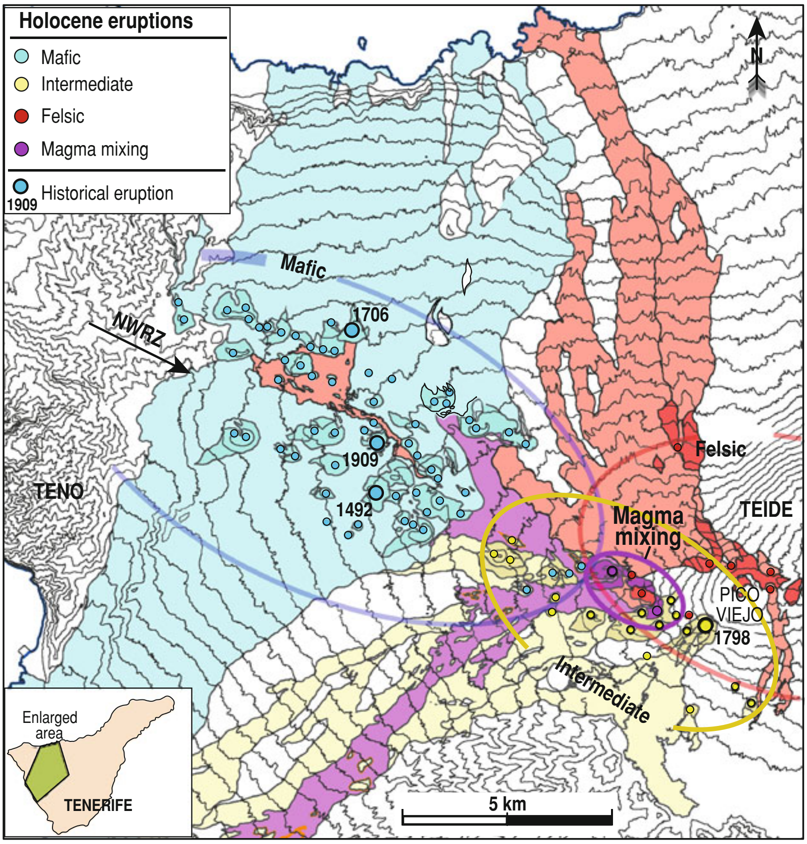


Fig. 4.15 Holocene volcanism in the NW rift zone demonstrating the characteristic groupings of eruptive vents along the crest of the ridge. Assuming a common mafic parent from the uppermost mantle, eruptions are spatially arranged according to composition, with basanites at the western (distal) end, and phonolites at the eastern (proximal) end, close to the shallow and differentiated magma reservoirs of Teide Volcano

attenuated, has continued until recent times, particularly in the proximal (SW) area of the rift, as underlined by ages of 37 ± 3, 33 ± 3, and 33 ± 1 ky (Carracedo et al. 2007), and even to historic times (e.g., the Fasnia and Arafo eruptions in 1705 A.D.).

4.4.4 The NW Rift Zone

Just as the deeply eroded NERZ provides relevant information for the understanding of the entire cycle of growth and mass destruction of rift zones, the NW rift, very active in the Holocene, gives significant details of the temporal and spatial distribution of surface volcanism and thus provides indirect information about the evolution and internal structure of the TVC magma system during its most recent volcanic cycle (Ablay et al. 1998; Carracedo et al. 2007; Wiesmaier et al. 2011).

The eruptive vents cluster in the characteristic pattern of rift zones at the crest of the rift, while lava flows extend down both flanks (Fig. 4.15). One of the most interesting features is the compositional distribution of eruptions, showing a distinct bimodal series, with basanite and phonolite, respectively as the distal and proximal end-members, and intermediate eruptions in the central part of the rift zone (Fig. 4.15). The petrologically distinct magmas evolved from a common primitive basanite parent by crystal fractionation (Ablay et al. 1998). The interaction of these two magmas, i.e., basanites with phonolites, that evolved separately in a shallow central chamber, led to spectacular examples of magma mixing (Araña et al. 1994; Wiesmaier et al. 2011).

4.5 Rifting and Landsliding in the TVC

The youngest lateral collapse (Icod) on the north flank of Tenerife occurred at ~200 ky, as documented by the age of the lava flows above the debris avalanche in the galería Salto del Frontón (two K/Ar ages of 195 ± 12 and 198 ± 5, and one Ar/Ar age of 192.3 ± 11, from same flow).

From swath bathymetry data, Watts and Masson (1995) inferred that the debris avalanche covered an area about 20 km wide and 105 km long. The tongue-shaped structure, suggesting high mobility, extends upslope towards a "chute-like", apparently erosive feature in the Icod Valley and the Caldera de Las Cañadas (Fig. 4.16).

The nature of the collapse is still not fully resolved (i.e., vertical versus lateral). The vertical collapse is believed to have formed from several classical (vertical) caldera collapses between 1.2 and 0.17 My (e.g., Ridley 1971; Booth 1973; Martí et al. 1994; Bryan et al. 1998). On the other hand, a range of authors have proposed that the present day Las Cañadas Caldera is primarily a landslide scar (Navarro Latorre and Coello 1989; Ancochea et al. 1990, 1999; Carracedo 1994; Watts and Masson 1995; Urgeles et al. 1997, 1999; Masson et al. 2002). In fact, strong evidence exists for a lateral collapse (landslide) at around 200 ky, which is clearly linked to submarine debris avalanche deposits (Fig. 4.16). The point has been made on experimental grounds that repeated (vertical) caldera collapses can weaken the surrounding crust and create a "spider-web"-like arrangement of faults inside and outside a collapse caldera (Walter and Troll 2001; Troll and Schmincke 2002). These authors have argued that in the case of ocean islands, where coastlines represent un-buttressed free surfaces, entire "cake slices" may break out of an island's edifice by lateral instability once a system of radial and concentric weaknesses has been established (Troll and Schmincke 2002). Therefore, the combined effects of vertical and lateral collapses may have given rise to the present-day Las Cañadas Caldera, the most recent modification being the Teide and Pico Viejo complexes that currently grow inside the scar of the 200 ky (lateral) Icod collapse, which in turn, likely exploited older instabilities in the Las Cañadas edifice.

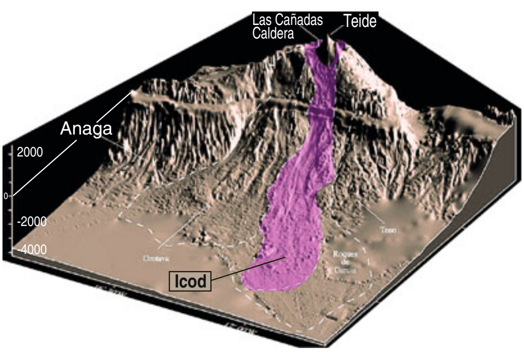


Fig. 4.16 3D representation of the north flank of Tenerife, viewed from the northwest, showing the successive lateral collapses. The youngest (Icod) is indicated in a different colour. Note the extension upslope of the debris avalanche towards the southern wall of the Cañadas Caldera, interpreted as the headwall of this giant landslide. Teide Volcano is nested in the Icod collapse depression (from Watts and Masson 1995)

A continuous layer of debris avalanche deposits extends inside the Las Cañadas Caldera below the present Teide stratocone (Márquez et al. 2008), providing strong support for a landslide origin of the currently visible depression.

The relevant aspect of this collapse event is that it formed a general spatial and temporal basis for the TVC and had a direct role in its construction and in promoting the magmatic variability present in the current volcanic complex.

4.6 Rifting, Landsliding and Magmatic Variation

A comparative analysis of the evolution of different Canarian rift zones, including those of the TVC, outlines notable common characteristics. Rifts are recurrent features that show cyclic

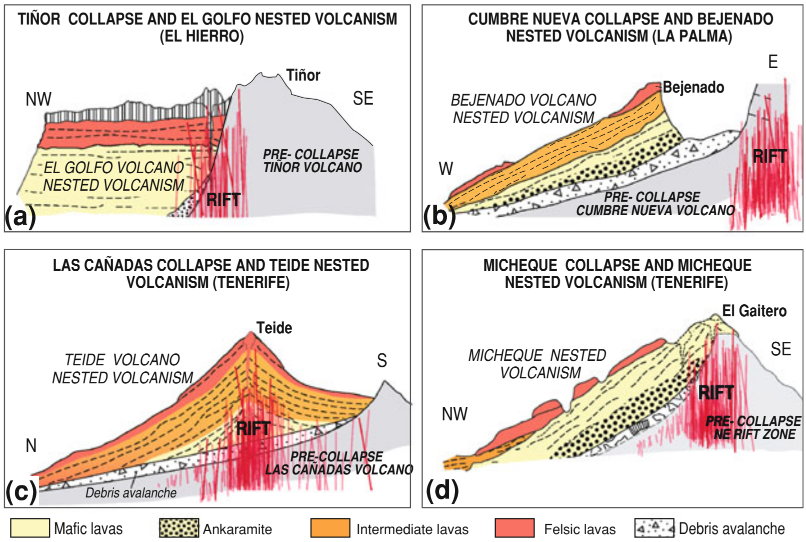


Fig. 4.17 Examples in the Canary Islands of rifts and associated landslides with subsequent nested differentiated volcanism. Note that progressive magmatic differentiation takes place in the sequences filling the landslide scars (from Carracedo et al. 2007)

patterns of growth, instability, flank collapse, nested volcanism, and eruptive decline and dispersion (Carracedo et al. 2011).

Variations in magma composition appear to occur in response to lateral collapses in the Canaries (Fig. 4.17). A collapse implies disruption of an established feeding system of a rift, which allows dense mafic magmas to ascend to the surface by edifice unloading (Manconi et al. 2009). The result is the concentration of progressively centralized eruptions focusing in the interior of the landslide basin, thus progressively filling up the collapse scar (Carracedo et al. 2007, 2011; Longpré et al. 2009). The emplacement of magma at increasingly shallower depths within this nested volcanic edifice will allow for extensive modification of magma and will lead to progressively more differentiated eruptions, commonly reaching felsic compositions (trachytes, phonolites) that become more and more dominant due to the progressive increase in height of the volcanoes nested inside the landslide embayments.

Although felsic volcanic complexes in the Canaries may originate from a variety of processes (Wolff 1983; Pérez-Torrado et al. 1995; Troll and Schmincke 2002; Paris et al. 2005; Longpré et al. 2009), a considerable volume of differentiated volcanism in the Canaries appears to be associated with rift flank collapses that are followed by abundant and prolonged nested volcanism. Regularly, these eruptions evolve from initially mafic to terminally felsic compositions. Lateral collapses may consequently be considered to represent a major cause for structural and petrological variability in ocean islands (Carracedo et al. 2007, 2011; Longpré et al. 2009; Manconi et al. 2009), Teide being a prime example of this feature.

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